IN THE UNITED STATES
PATENT AND TRADEMARK OFFICE

PATENT APPLICATION

INVENTORS **Eric Bouillet**
Gang Liu
Iraj Saniee

CASE 3-5-1

Serial No. 09/805021

Group Art Unit 2633

Filed March 12, 2001

Title Design Method for WDM Optical Networks Including Alternate Routes for Fault Recovery

ASSISTANT COMMISSIONER FOR PATENTS

WASHINGTON, D.C. 20231

SIR:

DECLARATION UNDER 37 C.F.R. 1.131

1. I, Eric Bouillet, received a Ph.D. in Electrical Engineering from Columbia University. I am a former member of the technical staff at Bell Laboratories, Lucent Technologies Inc., Murray Hill, New Jersey, where I was employed in the Mathematics of Networks and Systems Research Department during at least a portion of the years 1999-2000.

2. I, Gang Liu, hold an M.S. degree in Optics from Beijing University and an M.S. degree in Computer Science from Columbia University. I am a former member of the technical staff at Bell Laboratories, Lucent Technologies Inc., Murray Hill, New Jersey, where I was employed in the Mathematics of Networks and Systems Research Department during at least a portion of the years 1999-2000.

3. I, Iraj Saniee, received a Ph.D. in Operations Research and Control from Cambridge University in the United Kingdom. I am Director of the Mathematics of Networks and Systems Research Department at Bell Laboratories, Lucent Technologies Inc., Murray Hill, New Jersey. I have been employed at Bell Laboratories since November 2, 1998.

We the Declarants, Eric Bouillet, Gang Liu, and Iraj Saniee, state further that:

4. In the above-referenced application, Eric Bouillet, Gang Liu, and Iraj Saniee each made an inventive contribution to the invention as recited in at least one of claims 1-20.

5. Prior to October 2000, at Murray Hill, New Jersey, we developed algorithms for designing survivable all-optical core networks with DWDM hardware. In particular, we developed three design architectures based, respectively, on routing with dedicated protection, routing on logical rings with shared protection, and routing on meshes with restoration. In a dedicated protection architecture, two distinct node pairs are prohibited from sharing the same protection wavelength on the same optical fiber, whereas such sharing is permitted in a shared protection architecture. In our architecture for routing on meshes with restoration, so-called "active" paths are constructed that carry the demands for all node pairs, and additional numbers of wavelengths are set aside for restoration of paths that are affected by failures. In all three architectures, a cost function is optimized.

6. We tested our algorithms in a series of simulations. The inputs to the simulations included information specifying the numbers and relative locations of nodes of a hypothetical network, the distances between the nodes, hardware and cable costs associated with nodes and links, and hypothetical demand matrices for the hypothetical network. These inputs represented a simulated, and not a real-life, situation. Nevertheless, the results of the simulations confirmed that our design algorithms would work as intended when used in a range of real-life situations of practical interest.

7. The abovesaid simulations included the successful operation of algorithms conforming to at least the following descriptions:

7.1 A routing method in an optical network, comprising:

a) logically subdividing a network into a plurality of rings, wherein each ring is formed by two link-disjoint paths between a pair of nodes;

b) to each of the demands, assigning a ring that contains both of the pertinent end nodes;

c) to each of the demands, assigning two mutually link-disjoint paths on the ring from one end node to the other, wherein one said path is a working path and the other said path is a protection path; and

d) assigning at least one wavelength channel to each working path and to each protection path, resulting in a working wavelength channel on the working path and a protection wavelength channel on the protection path.

7.2 The method of 7.1, in which each of the protection paths is node-disjoint from its corresponding working path.

7.3 The method of 7.1, further comprising, for at least one pair of end nodes, subdividing a total demand between said end nodes into a plurality of unit demands, and wherein the assigning of working paths and protection paths is performed on the unit demands.

7.4 The method of 7.3, wherein each link of the network comprises one or more optical fibers, and one unit of demand is equivalent to the bandwidth capacity of one wavelength channel on an optical fiber.

7.5 The method of 7.1, wherein each working path and each protection path is confined to a single ring.

7.6 The method of 7.1, wherein the assignment of wavelength channels is carried out such that no two demands have the same working wavelength channel or protection wavelength channel.

7.7 The method of 7.1, wherein the path and wavelength-channel assignments are carried out so as to drive down a cost function determined at least in part by the occupancy of wavelength channels on links of the network.

7.8 The method of 7.7, wherein the cost function is further determined by the occupancy of ports or optical termination units at nodes of the network.

7.9 The method of 7.7, wherein:

the links of the network comprise optical fibers,

the cost function includes, for each link, a cost component for placing a further wavelength channel on such link; and

said cost component is selected to decrease as the number of already-placed wavelength channels increases, but to jump to a highest value when the number of already-placed wavelength channels reaches the full capacity of one optical fiber.

7.10 The method of 7.9, wherein the cost function further includes a cost component for placing wavelength ports at end nodes of the link, and the cost component is selected to decrease as the number of already-placed wavelength ports increases, but to jump to a highest value when the number of already-placed wavelength ports reaches the full capacity of one optical cross-connect.

7.11 The method of 7.7, wherein the path and wavelength-channel assignments are carried out such that the assignments to the respective demands jointly drive down the cost function.

7.12 The method of 7.1, wherein each link of the network comprises one or more optical fibers.

7.13 The method of 7.1, wherein:

each link of the network comprises one or more optical fibers; and

the assignment of wavelength channels is carried out such that on a given ring, the protection paths of two or more demands are permitted to share the same wavelength channel if the respective working paths of said demands have no common link on the given ring.

8. Each of descriptions 7.1-7.13 relates at least one of the dedicated protection or shared protection architectures as indicated in the table below:

Dedicated Protection	Shared Protection
7.1-7.12	7.1-7.5, 7.7-7.13

9. Attached Exhibit A is a portion of an internal Lucent Technologies Technical Memorandum having document numbers 10009664-xxxxxx-01TM, 10009626-xxxxxx-01TM. The document numbers have been partially redacted to conceal the date. The document date was prior to October 1, 2000. Lucent Technical Memoranda are published internally, in accordance with company policy, to disseminate research results within the company.

10. Exhibit A describes, among other things, network design and routing methods that conform to the descriptions in 7.1-7.13 hereinabove. Moreover, Exhibit A includes, at page 29, a Table 6.1 which presents results of the simulations mentioned above. More specifically, the first two "results" columns of the table relate to dedicated protection, the second two relate to shared protection, and the last two columns relate to routing on meshes with restoration.

11. Herein, each of Declarants Eric Bouillet, Gang Liu, and Iraj Saniee individually certifies that all statements made of his own knowledge are true and that all statements made on information and belief are believed to be true. Each of the Declarants makes this certification with the understanding that willful false statements and the like are punishable by fine, imprisonment or both under 18 U.S.C. 1001 and that willful false statements and the like may jeopardize the validity of the application-at-issue or any patent issuing thereon.

Date: 1/5/2005 ______________________ Eric Bouillet

Date: ____________ ______________________ Gang Liu

Date: ____________ ______________________ Iraj Saniee

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Date: ______________ ______________
Eric Bouillet

Date: 1/11/2005 ______________
Gang Liu

Date: ______________ ______________
Iraj Saniee

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Date: ______________ ______________________
Eric Bouillet

Date: ______________ ______________________
Gang Liu

Date: Jan 11, '05 ______________________
Iraj Saniee

US Patent Application Serial No. 09/805021
Bouillet-Liu-Saniee 3-5-1
Declaration Under 37 CFR 1.131

EXHIBIT A

Lucent Technologies
Bell Labs Innovations

Document Cover Sheet for Technical Memorandum

Title: Algorithms for DWDM Mesh Network Design: Routing and Wavelength Assignment for Dedicated Protection, Ring Auto-Recovery and Optical Cross-Connect Restoration in Core Optical Networks

Authors	Electronic Address	Location	Phone	Company
Eric Bouillet	boe@lucent.com	MH 2C-179	908-582-4054	
Gang Liu	gangliu@lucent.com	MH 2C-306A	908-582-1713	
Iraj Saniee	iis@lucent.com	MH 2C-300	908-582-6410	

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10009626-	-01TM	20878	MA300022030
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Keywords: all optical networks, routing of optical channels, routing and wavelength assignment, network design, ring design, mesh restoration, dedicated and shared protection in DWDM networks, path restoration, spare capacity assignment.

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Abstract

This report describes algorithms for designing survivable all-optical core networks with dense wavelength division multiplexing hardware. Three design architectures are presented that are based on 1. routing with dedicated protection, 2. routing on logical rings with shared protection and 3. routing on meshes with restoration. Each one of these architectures optimizes a specific metric. Several critical metrics which quantify both cost and flexibility, *e.g.*, total active and protection wavelengths, port counts, fiber and wavelength miles, are defined and calculated for each design alternative for a sample (real) network. In the context of core and long distance networks, wavelength interchange and cross-connection at intermediate nodes are allowed and the cross-connect port counts are calculated. In the context of metropolitan networks, the routing and wavelength assignment problem is discussed for logical rings. Some of these architectures have been studied with regards to previous technologies such as SONET, SDH and DS1/DS3 networks. This work, on the other hand, is focused especially at DWDM, and the novelty of the techniques described here rests on their applications to DWDM and their quality, near-optimality and run times in this new context. Operational issues for implementation of each solution, and parameters such as recovery times in cases of single network failures, are also discussed with reference to each proposed architecture.

Pages of text: 32 Other pages: 2 Total: 34
No. Figs.: 4 No. Tables: 10 No. Refs.: 51

Algorithms for DWDM Mesh Network Design:

Routing and Wavelength Assignment for Dedicated Protection, Ring Auto-Recovery and Optical Cross-Connect Restoration in Core Optical Networks

Eric Bouillet, Gang Liu, Iraj Saniee
Bell Labs Research

Abstract

This report describes algorithms for designing survivable all-optical core networks with dense wavelength division multiplexing hardware. Three design architectures are presented that are based on 1. routing with dedicated protection, 2. routing on logical rings with shared protection and 3. routing on meshes with restoration. Each one of these architectures optimizes a specific metric. Several critical metrics which quantify both cost and flexibility, *e.g.*, total active and protection wavelengths, port counts, fiber and wavelength miles, are defined and calculated for each design alternative for a sample (real) network. In the context of core and long distance networks, wavelength interchange and cross-connection at intermediate nodes are allowed and the cross-connect port counts are calculated. In the context of metropolitan networks, the routing and wavelength assignment problem is discussed for logical rings. Some of these architectures have been studied with regards to previous technologies such as SONET, SDH and DS1/DS3 networks. This work, on the other hand, is focused especially at DWDM, and the novelty of the techniques described here rests on their applications to DWDM and their quality, near-optimality and run times in this new context. Operational issues for implementation of each solution, and parameters such as recovery times in cases of single network failures, are also discussed with reference to each proposed architecture.

1 Introduction and Overview

We describe algorithmic techniques and their computational runtimes to design core (mesh) networks carrying large amounts of demand using DWDM systems in which 100%, or any desired degree of, fast recovery is required for a *single* network *node* or *link failure*. In this report we address only *static* network designs utilizing *protection*, *recovery* and *restoration* schemes, but many of the ideas and methods presented lend themselves to *dynamically reconfigurable* DWDM networks applicable to metro, enterprise and access network segments also. These algorithms exploit not only existing or projected capabilities of (Lucent) DWDM systems but they also point to desired hardware functionality that could be built if the gains in design quality, as reported here, warrants such an investigation. The strength of each design mechanism lies not only in its resulting network *cost*, which is measured based on several defined metrics, but its simplicity or complexity, and also the speed of execution of the proposed mechanism in operational networks, which are also described.

Key characterizing features of each design, *e.g.*, the number of optical cross-connects (OXC) devices and wavelength converters needed at each node, and the number of redundant channels needed for 100% recovery from a single network failure, are complemented by several other metrics. These include the total number of links used, number of fibers per link, (maximum) number of wavelengths, or λs, in a link, (maximum) number of cross-connects and wavelength converters in any node, total fiber-pair kilometer, total λ kilometer for both active and protection λ s, and the total number of cross-connect ports.

For prior work on design of networks using SONET rings see [2-4,7,12,21-30,36,39-40,45], for wavelength assignment and routing see [6,9,11,13,15,17,25,34,35,37,43,50], for general network design see [8,10,14,19,22,27,32,46,48], for multicommodity flow approximations see [5,33,41,42,47,49] and for applications of multicommodity flow optimization to circuits restoration in communication networks see [5,51]. The following four sections describe the common assumption for the three architectures and give examples for each.

1.1 Summary of assumptions and architecture definitions

The DWDM core network designs schemes described in this report utilize:

- Pre-planned *dedicated* active and protection wavelengths on shared fibers assigned between node pairs which have demands
- Pre-planned active and dedicated or *shared* protection wavelengths assigned between nodes lying on (carefully) selected DWDM logical rings with shared fiber
- Pre-planned active and restoration paths with *shared* protection wavelength assignments stored as optical cross-connects maps that are invoked during failures

The underlying assumption for all three design schemes for core optical networks described is that 1. each node is equipped with optical cross-connect devices and 2. wavelength converters are available where DWDM systems terminate and wavelengths are segregated. A typical node is shown in Fig. 1.1.

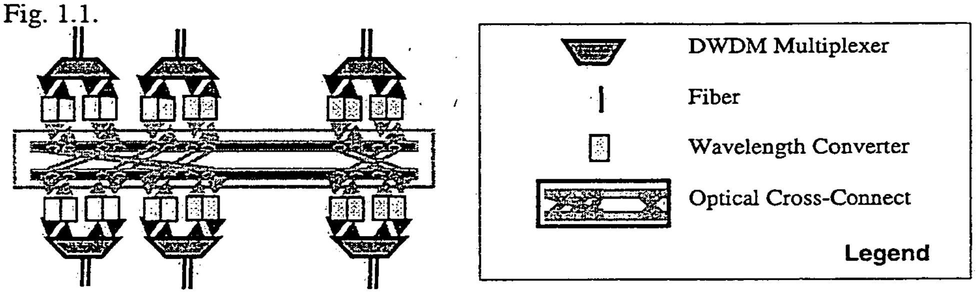

Figure1.1 Configuration of each network node for a simple 2-wavelength DWDM system

It is assumed that the number of wavelengths carried on each fiber is a fixed value, which currently runs from 40-80 wavelengths (for both Lucent and other vendor equipment) but soon may reach 160 and higher values. Demands between nodes are given in units of wavelengths, or λs, each of which may carry a fixed bandwidth. Currently this fixed bandwidth is one of STS16/STM4 (~600mbps), STS48/STM16 (~2.4gbps) or STS192/STM64 (~10 gbps).

1.2 Dedicated protection architecture

In this architecture any node pairs which have demand are connected with sufficient number of wavelengths on an active path and an identical number of protection wavelengths on a diversely routed protection path. The protection wavelengths are not shared and are *dedicated* for each node pair, but the fibers carrying active or protection wavelengths for different node pairs may be shared. This is illustrated in Fig. 1.2. Notice that although the fiber on link 1-3 is shared for protection of demands 2-4 and 3-8, the protection wavelengths will be distinct. Use of optical cross-connects reduces the number of wavelengths needed and optical cross-connect patch panels are adequate for creation of such designs, since real time re-arrangements are not required as long as demands are kept fixed.

1.2.1 Dedicated protection recovery scheme

The scheme for recovery from link failure is easily seen to require 1. recognition of the failure by each affected end node pair, and 2. switching to the dedicated protection wavelength(s) by each

end node pair. For each wavelength, therefore, the equipment used at end nodes perform an operation identical to Automatic Protection Switching (APS) available in the earlier SONET and SDH hardware technologies. The speed of recovery is thus a few tens of milliseconds.

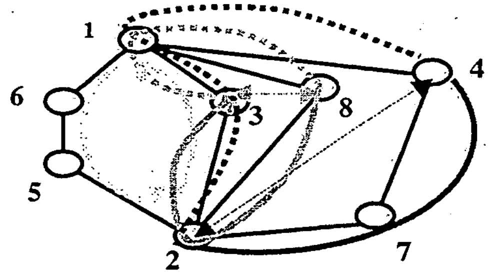

Figure 1.2 Diversely routed protection wavelengths (dotted lines) for demands between node pairs 1&2, 2&4 and 3&8 using active wavelengths (solid lines) are shown. These wavelengths (active or protection) can share fiber, *e.g.*, on links 1-3 & 2-3.

1.2.2 Solution methodology

The solution methodology consists of finding a disjoint pair of active and protection paths for each demand, aggregating these to obtain the total number of wavelengths on each fiber, and then costing the overall design. Phase 1 can be carried out in at least two ways. For example, each demand can be routed on its "shortest path" (*e.g.*, by counting hops or distances, or use of an adaptive cost metric which keeps track of the "fill" of a fiber) and dedicated protection wavelengths are routed over the disjoint residual graph. Alternatively, all node pairs with their disjoint routes can be routed simultaneously using a cost-adaptive approach. Details of the algorithmic issues are discussed in Sections 2 and 3.

1.3 Shared protection architecture using logical rings

In this architecture node pairs are grouped into logical DWDM rings each of which carries no more than the pre-defined number of wavelengths per fiber for active as well as protection wavelengths. *Active* paths are defined for all node pairs on the same logical ring and protection wavelengths are reserved in the complementary routes on the ring for each node pair, as shown in Fig 1.3. The number of protection wavelengths for each demand is thus the same as the number of active wavelengths used for carrying demands allocated to each ring. However, non-overlapping demands on the same ring can *share* protection wavelengths. For example, demands between nodes 1-3 and 2-3 can share protection wavelengths on the ring 1-3-2-5-6-1. The rings 1-4-7-2-5-6-1 and 1-3-2-5-6-1 can share fibers on links 2-5, 5-6, and 6-1. Although in principle it is possible to share protection wavelengths *across* rings through the use of optical cross-connects, we do not use such sharing due to the complexity of recovery when failures occur.

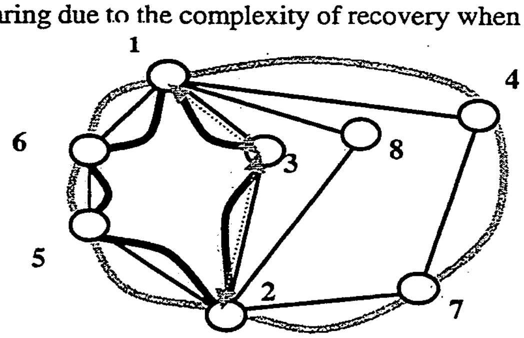

Figure 1.3 Protection wavelengths for demands between 1&3 and 3&2 on ring 1-3-2-5-6-1 can be shared, as can the fibers on links 2-5, 5-6 and 6-1 for the two rings 1-4-7-2-5-6-1 and 1-3-2-5-6-1, as shown

1.3.1 DWDM rings auto-recovery scheme

The scheme for recovery from failure is only somewhat more complex than dedicated protection described above. Similar to dedicated protection, the end nodes of each wavelength affected by the failure need to take note of the failure. Once this condition is recognized, the switch over to protection wavelengths is made. In our ring design solution, each demand is mapped to a single ring. Therefore it will not be necessary to coordinate multiple rings for recovery. The single ring auto-recovery is believed to be ~50 milliseconds, which is the recovery time for this logical ring design. Optical cross-connects are needed for auto-recovery on each logical ring. Optical cross-connects are needed when logical rings share fibers.

1.3.2 Solution methodology

The solution methodology consists of partitioning demands into a set of logical rings. The routing of the demands within each ring is the well-known routing and wavelength assignment problem on rings [7,36,38,39,40,44,45] for which novel, efficient and near-optimal solutions are given in this paper. Repeated application of this method on each logical ring gives the number of λs on each fiber for each ring, the sum of which over all rings provides the solution. Details are described in Sections 2 and 4.

1.4 Shared protection architecture using restoration on meshes

This architecture generalizes the shared-protection ring scheme described above, without requiring partition of demands into logical rings. In this scheme, *active* paths are constructed that carry the demands for all node pairs. Additional numbers of wavelengths are set aside for *restoration* of paths that are affected by a failure. The additional capacity is simply the maximum number of wavelengths required on each link when failures occur, one at a time, and overflow capacity has to be routed through the rest of the network. The exact decision as to what restoration routes to use for each failure is an off-line decision that can be either pre-planned or discovered by the network elements via an appropriate protocol. This scheme *optimizes* the redundant (or spare) capacity requirements. The price paid for this optimization is in the increased complexity of operating such a network, and the automation of the restoration procedure and its speed of execution. Fig. 1.4 shows a simple example in which protection path 2-3-1-8 for demand 2-8 on path 2-8, protection path 2-3-1-4 for demand 2-4 on path 2-7-4 and the active path 1-3-2 for demand 1-2 on path 1-3-2 all can share wavelengths on edges 2-3 and 3-1.

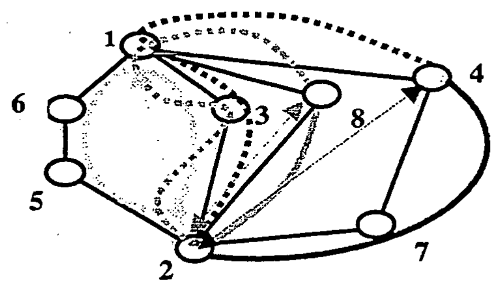

Figure 1.4 Active and restoration paths and wavelengths for demands between nodes 1-2 (1-3-2 and 1-6-5-2), 2-4 (2-7-4 and 2-3-1-4) and 2-8 (2-8 and 2-3-1-8)

1.4.1 Restoration scheme

This scheme requires pre-planning for an efficient implementation. Each failure invokes a reconfiguration map at each node with possible wavelength conversion to avoid collision on the same set of links during path restoration events. The maps are pre-computed using optimization. The objective is to minimize the total number of wavelengths needed. Such maps are stored in

each optical cross-connect. Path restoration is not conditional on isolation of fault: by using multiple alternative *disjoint* protection paths for each active path, the end nodes initiate recovery procedure once the signal loss is registered and disjointness of restoration routes ensure their availability when the single failure condition disables the normal route(s). Once the end nodes encounter a failure condition on a path, they communicate the restoration routes of the λs to be restored to each intermediate OXC on alternative paths and the maps to be uploaded by each OXC. These maps need not change until new demands are added to the network in which case delta-updates will be necessary. In case of topology changes, all active and backup routes may require updating, but topology changes surely affect other architectures too.

1.4.2 Solution methodology

The solution methodology consists of first finding *k*-shortest disjoint paths for each demand, and then solving a multicommodity (integer) linear programming problem posed over the pre-computed paths. A variety of cost functions can be optimized in this approach and we found the total λ*km gives the best solutions for the problems studied. Algorithmic details are described in Sections 2 and 5.

1.5 Outline of report

In Section 2 we provide a more formal setting and give definition of the problems that are studied together with the general input/output and notations used for problem formulations. In Sections 3, 4 and 5 we provide formulations and algorithmic details of each of the three architectures described in Sections 1.2 through 1.4. In Section 6 computational results are presented that compare and contrast these solutions for the sample network of Section 2.6.

2 Problem Description and Notation

Figure 2.1 shows a schematic of the different problems that we solve to obtain DWDM designs with a variety of protection wavelength sharing mechanisms. These problems, their inputs and outputs and their optimization objectives are described below.

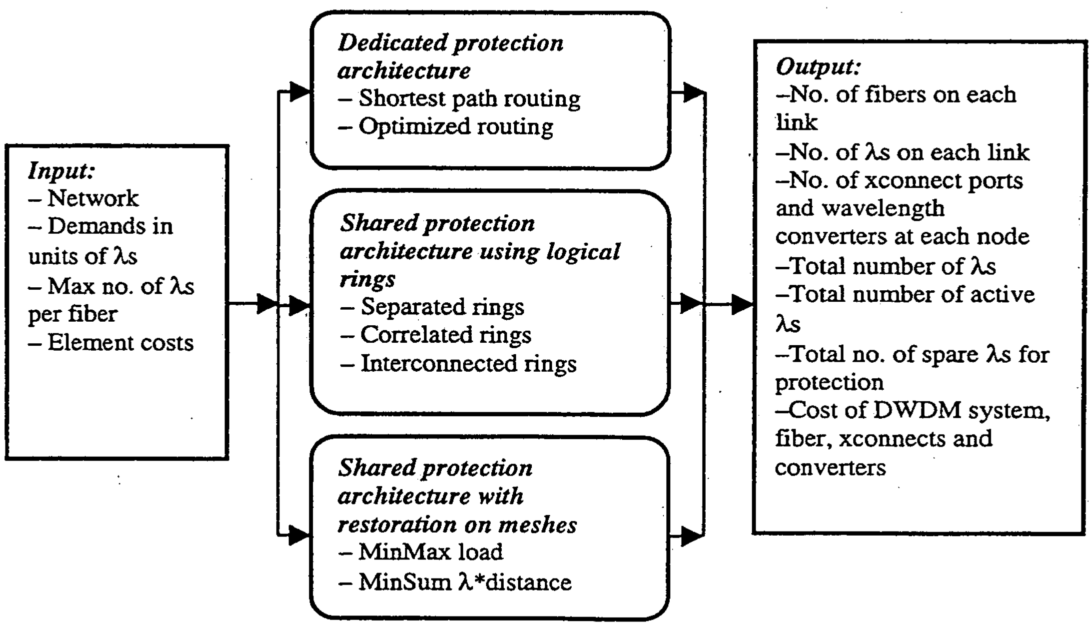

Figure 2.1 Schematic of problems solved

2.1 Terminology

A **wavelength** refers to a frequency in the optical spectrum [48]. A **λ-channel** implies the activation (reservation) of a wavelength set along one direction of one fiber-pair. All λ-channels are expressed in terms of the same unit (we assume in the remainder of this report that the waveband of an STM-16 is the unit, *i.e.* one unit of λ-channel, or one unit of waveband, corresponds to the bandwidth of one unit of STM-16). An **optical connection** or **circuit** is a succession of one or more λ-channels in series. If **wavelength continuity** is imposed, all the λ-channels constituting the optical connection or circuit must be tuned to the same wavelength. This is a reasonable constraint in **metropolitan networks**, where distances are relatively short. In **core networks** with long distances, a channel can change wavelengths at intermediate points using **wavelength converters** and optical cross-connects, **OXCs**, that will be available at every node (see Fig 1.1). Once a wavelength channel is already assigned to a working circuit, this wavelength in the same fiber can no longer be assigned to any other (either working or protecting) circuit. Each active circuit should have a (disjoint) **protection circuit** for 100% (or a pre-defined percentage for each demand) recovery from single failures. A protection circuit may be dedicated for a specific active circuit, as is done in **dedicated protection,** in which case no sharing of wavelengths on any fiber takes place, even for protection channels. If one or more wavelengths in the same fiber are assigned as protection channels to multiple active paths, this is called **shared protection. Path protection** is protection of a circuit end-to-end, so that when the end nodes recognize failure of an active circuit, they can initiate a switch of the whole active path to another. **Path restoration** is the *process* of path recovery, *e.g.* the process used in 1+1 dedicated protection via Lucent's OTUP (see Section 2.2.1), automatic protection switching or APS, used in SONET, or mesh path restoration protocols.

2.2 Problem descriptions

The solutions we provide are best characterized by how optical protection channels are determined. As shown in the diagram in Figure 2.1, these fall into three categories:

1. **Dedicated protection (1+1)**: Pre-planned dedicated active and protection wavelengths on shared fibers are assigned between node pairs which have demands. Each circuit will be routed on two disjoint paths, one path is the working (active) path, and the other is for protection. The protection path is activated only if the working path fails. In general, wavelength continuity is not assumed for this architecture. Thus, when a circuit–a set of wavelengths in tandem–is assigned to a node pair with demand, it is treated as occupied by this circuit, *i.e.*, other circuits can no longer use any of the constituent wavelengths again, even in the absence of a failure. In this case cross-connect maps are fixed and require no re-arrangements except at the end nodes. It is possible to demand wavelength continuity for the dedicated protection architecture, *e.g.* for metro applications and that may involve additional wavelengths and more fibers.

2. **Shared protection based on rings (1:N):** Pre-planned dedicated or shared active and protection channels are assigned to nodes lying on (carefully) selected DWDM rings. The allocation of demands to rings makes it possible to share their protection channels, thus reducing the total number of channels needed in a network. A single link failure can only affect at most one circuit out of a set of non-overlapping working circuits and, as a result, a set of non-overlapping working circuits are able to share their protection channels within that ring. Wavelengths are not shared across rings, for active or protection channels. However, depending on whether rings share fibers (*separated* rings do not while *correlated* rings do) or demands are routed over single rings or multiple rings (each demand is assigned to a single separated or correlated ring while in *interconnected* rings a demand may go across multiple rings) different ring selections are possible. In this case cross-connect maps are also fixed

and either general OXCs (in shared fiber rings) or special-purpose *2x2* wavelength-selective OXCs (in dedicated fiber rings) are needed at every node. This solution can assume both wavelength continuity, in which case routing and wavelength assignment algorithms must be used, or take advantage of wavelength conversions at OXC terminations.

3. **Shared protection based on mesh restoration (1:N):** Pre-planned active and restoration paths are assigned to node pairs with active channels and protection channels available based on wavelength sharing across the network. In this case, wavelength assignments are stored in optical cross-connects as maps that are invoked based on end node-pair recognition of fault in their active circuits. In this case cross-connect maps are not fixed and may require re-arrangements at every node, based on end node pair request. However, restoration maps are pre-computed and stored in each optical cross-connect. This solution typically does not call for wavelength continuity because it relies on OXCs for its implementation and OXCs perform wavelength conversion for every wavelength.

2.3 Description of common inputs

N	Set of all network nodes
E	Set of all network edges
$G=(N,E)$	Graph of the network
K	Set of node pairs
W	the number of wavelength channels each fiber can carry
D	Set of all node-pair demands
d_k	Demand for node pair k in units of λs
L	The edge length matrix
$l_{ij}=l_e$	Length of edge e=(i,j)

2.4 Description of outputs

- **Routing:** Working and protection paths for all demands.
- **Load:** The number of wavelengths, φ_{ij}, used in each link (i,j) or x_p the number of wavelengths on a path p.
- **Wavelength assignment:** Assigned wavelength to each circuit.
- **Fibers required:** The number of fibers, f_{ij}, installed on each link (i,j).
- **Total fiber length:** The total length of fibers required.
- **Cross-connects for each node:** The number of cross-connects and their size at each node.

2.5 Cost function objectives and sub-objectives

The general optimization criterion is network cost. To minimize the total cost of the network, we can define a variety of terms for the objective function. These include cost of DWDM muxes, fibers, wavelength converters, and optical cross-connects. Minimizing one or more of the following can approximate minimization of the total cost of the network:

- The total length of fibers used in the network
- The total number of cross-connects used in the network
- The total "length" of all wavelengths used. This will have the effect of minimizing fiber lengths and cross-connect sizes

These cost components are combined in a variety of ways for each architecture, s described below.

2.6 *Example network*

To evaluate the effectiveness of the DWDM design techniques outlined in the previous sections, we apply them to a typical long distance core network. The results of these runs are summarized in Section 6. This network consists of 29 nodes, 53 links and 138 node-pairs with demands. Demands are in units of λ s. Static demands are assumed with linear growth quintupling in 4 years. The connectivity, demands and distances are given in the Figure 2.2 and Table 2.2.1 and Table 2.2.2, respectively.

— REDACTED —

Figure 2.2 Sample network

— REDACTED —

Table 2.2.1 Demand matrix in units of λ for year 1 (year x demand is year1 demand times x)

— REDACTED —

Table 2.2.2: Distance matrix

3 Design of Mesh DWDM Networks via Dedicated Protection

3.1 Outline

In this section we present an algorithm to find near optimal optical configurations (meeting lowest equipment cost requirements) for WDM mesh network infrastructure, while provisioning 100% protections against single equipment failures. We express the problem as a minimal fiber capacity allocation and wavelength routing problem. Although we allow wavelength conversions everywhere in the network, we favor solutions that maximize wavelength continuity in an attempt to minimize the number of wavelength converters.

3.2 Problem description

3.2.1 Description of additional inputs and variables used in the algorithm

In addition to the input parameters introduced in Section 2.3, the algorithms described below use the following parameters:

- A *NxN* incremental (per unit of fiber) cost matrix $C=[c_{ij}]$ whose entries indicate the fixed cost of installing one new (unidirectional) fiber strand on each link (i,j). We assume that the cost of installing a new fiber is a function of the length of the fiber (determining factors being cost per unit distance, and maximum distance between regenerators), and the cost of upgrading the OXC's. In the current model we use:

  $$c_{ij}=C_m\ell_{ij} \qquad (3.1)$$

  In (3.1.) C_m is the cost per unit distance and ℓ_{ij} is the length of the link (i,j). This cost model does not dependent on the number of pre-existing fibers; in practice installing the first fiber may be more expensive since the operation usually requires installing a new link-

infrastructure (green-field network design). We can easily extend the model to incorporate the cost of installing the first fiber by mean of a fiber-dependent cost function.

- A *NxN* incremental (per unit of λ-channel) cost matrix $H=[h_{ij}]$ whose entries indicate the fixed cost of installing the equipment for an additional (unidirectional) λ-channel between each node-pair. This cost should reflect the cost of installing the new OTUs and also the cost of the regenerators.
- A *NxN* optical configuration matrix $\phi^n = [\varphi^n_{ij}]$ whose entries indicate the number of (unidirectional) λ-channels used in each link connecting a node-pair as obtained at the end of iteration n of the optimization algorithm. This matrix is a variable to be optimized. Initially (n=0) all the entries are set to 0.
- A *NxN* fiber-count variable matrix $F^n=[f^n_{ij}]$ indicating the number of (unidirectional) fibers installed between the node-pairs ($f^n_{ij}=0$ if $\ell_{ij}=\infty$) at iteration n. We allow the case $f^n_{ij}\neq f^n_{ji}$ during the optimization process, but the final solution (last iteration) should have all $f^n_{ij}=f^n_{ji}$. Each fiber can carry up to W λ-channels (a typical value, which is used in the examples here, is W=80.) This matrix is another variable to be optimized. Initially (n=0) all the entries are set to 0. Clearly, $f^n_{ij} = \lceil \varphi^n_{ij} / W \rceil$
- A *NxN* marginal cost matrix function $Z(\phi^n)=[z_{ij}(\phi^n)]$ indicating for every link the cost of setting up a new λ-channel over an existing optical configuration ϕ^n. A typical cost should reflect the cost h_{ij} of installing the new channel and eventually the cost c_{ij} of adding a new fiber if φ^n_{ij} modulo W=0, that is, when the new channel would exceed the capacity W of an existing fiber. The model also accounts for the cost of installing (empty) unidirectional fibers in the opposite direction in order to match both directions with the same number of fibers (in order to form bidirectional fiber pairs). In the current model we use the following cost for comparison with the marginal cost $y_{ij}(\phi^n)$:

$$z_{ij}(\phi^n)=h_{ij}+\delta(\varphi^n_{ij} \bmod W)c_{ij}+[1+f^n_{ij}-f^n_{ji}]^+c_{ji} \tag{3.2}$$

  In (3.2.) δ(n) is the complementary indicator function which returns 1 if n=0 and 0 otherwise.
- For each node-pair (i,j) we assign a link weight $y_{ij}(\phi^n)$ which indicates a marginal cost of using link (i,j) when φ^n_{ij} λ-channels are already activated in the link. In contrast to the incremental cost $z_{ij}(\phi^n)$, the marginal cost is not the real cost of adding a new λ-channel in link $y_{ij}(\phi^n)$, but rather a qualitative value used by the algorithm to determine how desirable it is to use the link. The higher the value, the less desirable is the link. In this paper $Y(\phi^n)$ is a continuous approximation of the true cost $Z(\phi^n)$. See section "Model for Pricing" for the detailed description of $Y(\phi^n)$.
- A list of routes $R_{ij}=\{r^1_{ij}, r^2_{ij}, \ldots, r^m_{ij}\}$ for each node pair (i,j). The number of routes is no more than *m* and depends on the node-pair. This list is currently predetermined, depending on parameters given by the user (*e.g.* maximum number of routes and maximum number of hops in the route, in addition to minimum number of hops.)
  We currently use a K-shortest path algorithm to pre-compute the route-sets, in which the metric used is the link's weights $y_{ij}(0)$ (*i.e.* link weights for optical configuration $\phi^0=0$).
- For each route r and optical configuration ϕ^n, we define Length(r, ϕ^n) as the sum of the weight of the links along the route, that is

$$Length(r,\phi^n) = \sum_{(a,b)\in r} y_{ab}(\varphi^n_{ab}) \tag{3.3}$$

- For each route set R_{ij} and demand (i,j) we consider the vector $q_{ij}=\{q^1_{ij}, q^2_{ij}, \ldots, q^m_{ij}\}$ where each q^u_{ij} corresponds to the number d_{ij} units of wavelength using route r^u_{ij} (including wavelengths used for the protection.)
- We define $N_d(p, q)$ as the function that returns TRUE if paths *p* and *q* are node disjoint and FALSE otherwise.
- Similarly we define $L_d(p,q)$ as the function that returns TRUE if route p and q are link disjoints and FALSE otherwise. Note that if $N_d(p,q)$=TRUE then $L_d(p,q)$=TRUE, but the converse is not always true.

3.2.2 Objective

The objective of the algorithm is to compute the optical-connections (working and protection) for every demand such that the total network cost of the induced equipment is minimized. The total cost is a function of the amount of optical fiber, number of λ-channels, and size of the OXC's that are required to realize the optical configuration, *i.e.*:

$$Cost^n=\sum f^n_{ij}\, c_{ij} + \sum \varphi^n_{i,j}\, h_{ij} + \sum c_{oxc}(n_i)$$

Where n_i represent the number of λ-channels terminating at node *i*, and $c_{oxc}(n)$ is the cost function of the OXC's. For the sake of simplicity we have not mentioned the cost of the OXC's in our notation. In the current implementation of the algorithm we actually included the cost of the cross-connects (OXC-256, or OXC-1024) in the cost function using a trivial transformation: we represent every OXC as a unidirectional edge oriented from the node's input ports to its output ports, and let the utilization of the node be the number of λ-channels routed through the OXC. Then a cost function similar to the one used for the links is used for the nodes – with the exception that now a step in the cost function occurs when the number of wavelengths reaches the capacity of the OXC (instead of the capacity W of the fiber).

3.3 Link weighting for optimized routing

In this section we propose a model for weighting the link in correspondence to its utilization (number of λ-channels activated in the link). Based on the observation that it is more expensive to set up a new fiber than activating a λ-channel in an existing fiber, we suggest the following model:

- When the current occupation (number of active λ-channels) in a fiber is more than 0 and less than W, a new unidirectional λ-channel does not require setting up a new fiber, and the cost of using the link is h_{ij} (the cost of the OTU's for the new channel).
- When the number of active λ-channels modulo W is 0, activating a new λ-channel would require a new fiber, thus a cost $c_{ij}+h_{ij}$, where c_{ij} is the cost of the new fiber.
- In addition the model should also include the cost of adding fibers in the opposite direction (assuming that in the final solutions unidirectional fibers are paired together to form bi-directional fibers). Therefore the cost of adding a new λ-channel in link (i,j) is:

$$c_{ij}+h_{ij}+c_{ji}[1+f^n_{ij}-f^n_{ji}]^+ \tag{3.4.}$$

  In (3.4.) $c_{ji}[1+f^n_{ij}-f^n_{ji}]^+$ is the cost of adding unidirectional fibers in the opposite direction in order to match both directions with the same number of fibers.

Note that if a fiber contains only a few λ-channels, there is a waste of optical capacity which can be avoided by moving the demands to different routes that have enough spare capacity available to carry the λ-channels (*i.e.* do channel packing – or encourage fiber sharing). The cost function defined in (3.4.) fails to express the relative loss of not doing channel packing–using this model, once a new fiber is installed, the price of new λ-channels is independent of the utilization of the

fiber thus making under-used fibers no more expensive than fibers that are more heavily used. Here we introduce a more elaborate weighting function to include the utilization of the fibers into the model. An example of weighting function is shown in Fig.3.1 in parallel to the incremental cost function. The weight function decreases gradually as the number of channels increase in the fiber, until the capacity of the fiber is finally reached, at which point a new fiber becomes necessary (represented by a jump in both the cost function and the weight function). The advantage of this weight function is that under-used fibers appear more expensive than efficiently used fibers, thus making them less desirable from the point of view of a general optimization process. Another way to interpret the cost function is to imagine that every λ-channel participates in sharing the cost of the fiber, *i.e.*, the more λ-channel's in the fiber the less expensive is the cost per λ-channel.

We model the link's weight at iteration n by the following t-parameterized function:

$$y_{ij}^t(\varphi_{ij}^n) = \frac{\left(c_{ij} + c_{ji}\left[1 + f_{ij}^n - f_{ji}^n\right]^+\right)\left(1 - \frac{\varphi_{ij}^n \bmod W}{W}\right)}{\left(\varphi_{ij}^n \bmod W + 1\right)^t} + h_{ij} \qquad (3.5.)$$

The exponent t in the denominator of the weight function determines the shape of the function (when t increases the weight function converges to the real cost function – see Fig.3.1.) We currently use t=2.2 fixed – a value obtained empirically. Varying t from 2 to 3 by small increments during the optimization also seems to give relatively good results.

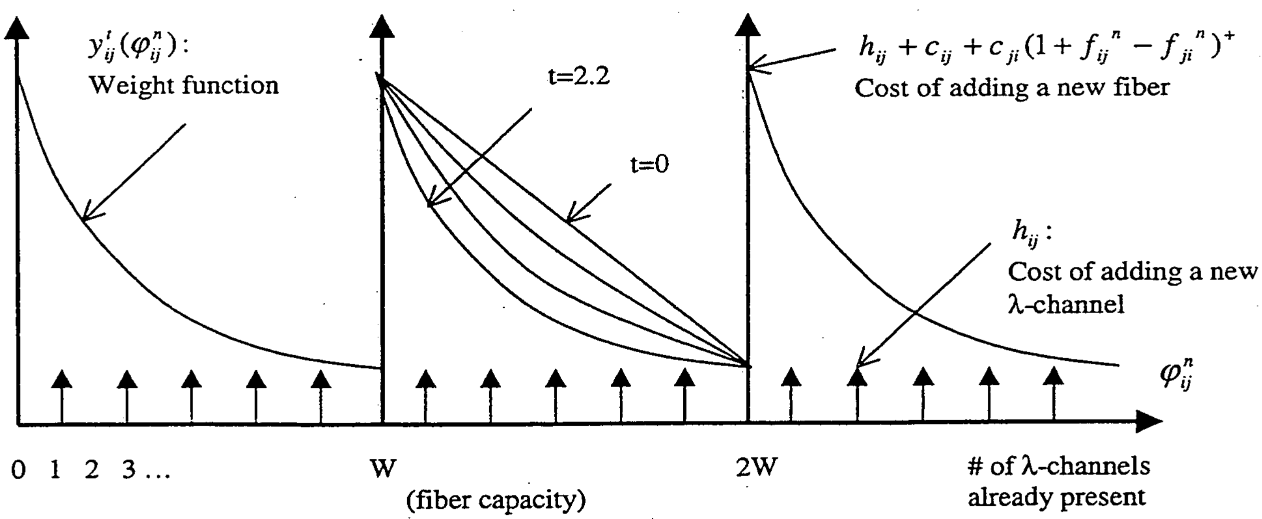

Figure 3.1 Pricing of λ-channels based on utilization and iteration parameter *t*

3.4 Algorithm

The following algorithm assumes single unit demands. In order to guarantee this assumption we decompose each demand (i,j) into d_{ij} independent one-units demands and view each one-unit demand as an individual demand, with its own working path and protection path.

The algorithm consists of three parts:

Part (1).

- In the initial step we assign the shortest node-disjoint route-pairs (working and protection paths) to the demands. We use the weight function $y_{ij}(\varphi^0_{i,j})$ for link lengths to compute the shortest paths (function presented in section 3.3.) Since there is initially no active λ-channel, the link weights are all $y_{ij}(0)$; that is for every non-zero demand d_{ab}, we find a route pair r^u_{ab} and r^v_{ab} in R_{ab} such that $N_d(r^u_{ab},r^v_{ab})$=TRUE (or $L_d(r^u_{ab},r^v_{ab})$=TRUE if there is no such route pair), and $\{r^u_{ab},r^v_{ab}\}$=arg min Length(r^u_{ab},0)+Length(r^v_{ab},0).
- We then update the link utilization, reserving a λ-channel in each link of every route pair of every demand d_{ab} (without constraint on wavelength continuity – as if wavelength converters were possible everywhere) and update F, ϕ^1, q^u_{ab}, q^v_{ab} and $Y(\phi^1)$ accordingly.
- Set iteration counter to n=1.

Part (2) is based on Baroni's [37] rerouting technique using the weight function $Y(\phi^n)$. The demands are first sorted in arbitrary order, which is preserved until the procedure completes.

- Sequentially, for every demand (a,b) – clear the λ-channels along the associated working path r^u_{ab} and protection path r^v_{ab}. Update F^{n+1}, ϕ^{n+1}, q^u_{ab}, q^v_{ab}, and $Y(\phi^{n+1})$'s accordingly – then find an alternate node disjoint route-pair $\{r^{u'}_{ab},r^{v'}_{ab}\}$ which minimizes Length($r^{u'}_{ab}$, ϕ^{n+1})+Length($r^{v'}_{ab}$, ϕ^{n+1}). Assign a λ-channel to this route-pair and update F^{n+1}, ϕ^{n+1}, $q^{u'}_{ab}$, $q^{v'}_{ab}$ and $Y(\phi^{n+1})$. Set iteration counter to n=n+1 and repeat for each demand.
- Repeat rounds of the previous step (using same sequence order) until convergence is reached.

Part (3) executes a path-coloring procedure (minimizing number of wavelength converters)

- A naive algorithm is described. In the following we list all the paths (working or protection) used by the demands. Repetitions of a same path may occur in the list if the path is used by several demands. We can either treat the working path and protection path of a demand as a single path using the same wavelength or we can treat them separately if working and protection paths can be assigned different wavelengths.
  - Sort the path list in decreasing order of number of hops.
  - Pick first path from the list and assign the first available wavelength to it
    - if no wavelength available, mark this path as requiring a wavelength conversion
    - remove the path from the list
  - Repeat the previous operation until all the paths have been removed from the list
  - If a wavelength could be assigned to every path, then stop, this is the solution.
  - Using a greedy heuristic (set-covering problem) place the minimum number of wavelength converters at node locations, such that all the paths marked as requiring a wavelength conversion contain at least one wavelength converter.
  - Break all the paths (marked and non-marked) into sub-paths such that no sub-path has a wavelength converter in it (except source and destination of path).
  - Repeat the algorithm with the new set of paths
- A more sophisticated algorithm is being investigated.

Other variants of this algorithm have been investigated:

- Randomly rearrange the order of the sequence between rounds in part (2).
- Sequentially reroute subsets of demands (instead of single demands) by removing all the demands of a selected subset at once and sequentially find a new shortest path for each removed demand - in arbitrary order. A possible subset can be all the demands

intersecting on an underutilized fiber. For instance if the fiber of a link uses only a few wavelengths, we can remove all the demands of that link and reroute the demands.

- A combination of two or more of the variants described above.

Out of all the variants described above, only the second one results in noticeable improvements at the expense of a longer run time.

3.5 DWDM network design using dedicated protection solution

We have experimented with the algorithm described above on the study network described in Section 2.9, using t=2.2 with 0.1 increments after each rerouting round for the weight function, and cost per lambda $h_{ij}=10^{-1}c_{ij}$. For comparisons we also show the shortest-path results (non-optimized solution obtained at end of Part 1, before the first round when all demands are assigned their shortest paths). See Section 6 for the results of the experiment.

4 Design of Shared Protection Based on Rings

4.1 Description of the problem

The problem is as described in Section 2 with notation and terminology described in Sections 2.3 and 3.2.

4.2 Description of proposed models

4.2.1 Correlated wavelength rings (CWR)

This scheme first identifies a set of rings from the given mesh network, such that all demands can be routed on at least one ring. Neighboring CWRs can share fibers, however, different active circuits must use different λ-channels. The objective is to minimize the total network cost. This results in a partially (1:n) shared protection model. Demands routed within the same ring may share protection wavelengths, while the demands routed in different rings cannot share wavelengths. As shown in Figure 4.2.1, circuits W_{16}, W_{62} and W_{21} can be routed in ring R_{1652} (counterclockwise λ-channel) and use the same wavelength λ_1, and share the clockwise λ-channel λ_1 in R_{1256} for protection. Circuits W_{34}, W_{45} and W_{53} can be routed in ring R_{2345} and be assigned to the same wavelength for working in clockwise λ-channel λ_2 in R_{2345} and share the counterclockwise λ-channel λ_2 in R_{2543}.

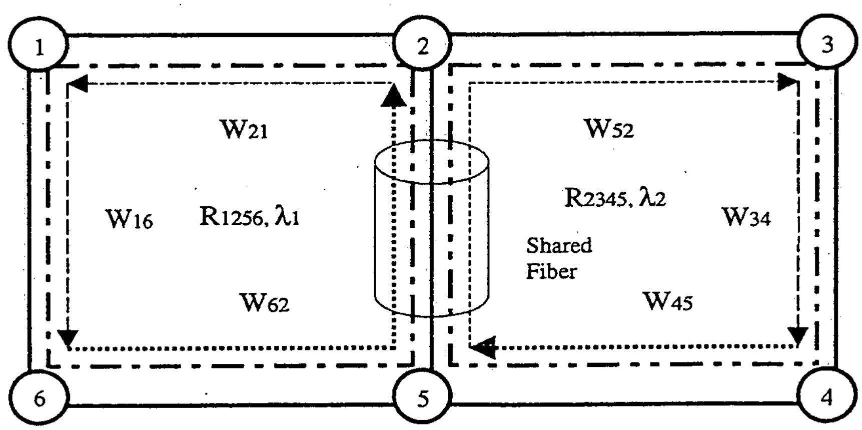

Figure 4.2.1 Correlated wavelength rings (CWR)

4.2.2 Separated fiber rings (SFR)

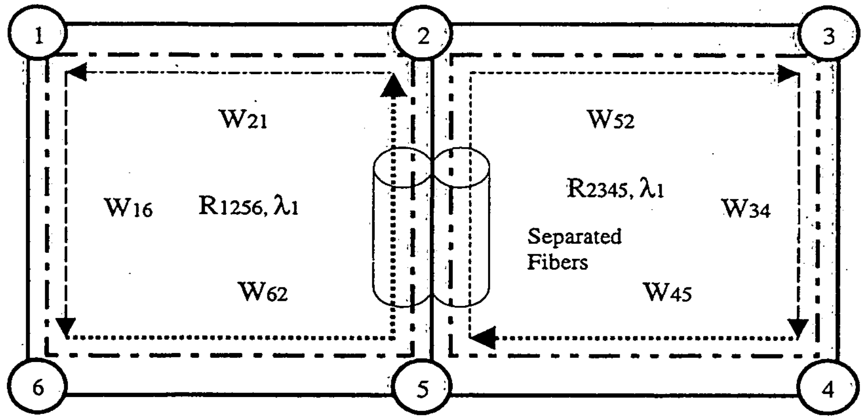

Figure 4.2.2 Separated fiber rings (SFR)

The CWR scheme allows shared protection via rings. However, the rings in CWR are virtual rings: they are wavelength rings rather than fiber rings. Some fiber ring oriented equipment and technologies are efficient and cost less, but they do not apply to CWR rings. Therefore, another scheme, separated fiber rings (SFR) may be used. A special case of SFR, where each ring contains precisely three nodes, has been discussed in [19].

The difference between SFR and CWR is the way fibers are shared among different rings. The CWR allows fiber sharing between neighboring rings, whereas each SFR uses dedicated fibers, as shown in Fig. 4.2.2. Since there is no fiber sharing in the SFR scheme, general-purpose cross-connects are not needed. This can result in reduced costs if the cost of *2x2* wavelength-selective cross-connects, which can be used for SFRs, is less than the cost of a general purpose OXC. Each demand is still routed on a single ring, and there are no interconnections among different rings. The SFR scheme, however, may have the following disadvantages:

1. Some rings may be too "large" for current technologies due to distances and perimeters involved.
2. Some rings may be very "thin" and have low fiber utilization, *i.e.*, the number of working wavelengths in a fiber ring may be very small compared to the fiber capacity.

4.2.3 Interconnected fiber rings (IFR)

The two disadvantages of SFR described above can be avoided by the Interconnected Fiber Rings (IFR) scheme. Suppose we have another demand W_{13}, as shown in Fig. 4.2.3, then a larger ring R_{123456} is needed to route the demand W_{13} for both CWR and SFR schemes. Alternatively, instead of adding the larger ring R_{123456}, we can first divide W_{23} into two parts, W_{12} + W_{23}, then route W_{12} in R_{1256} and W_{23} in R_{2345}, which we call the Interconnected Fiber Ring (IFR) architecture. Neighboring rings can be interconnected through OXCs in their common nodes. This scheme will allow us to split larger rings into smaller rings thus helping avoid the use of "large" (in diameter) and "thin" (in utilization of available λs) rings.

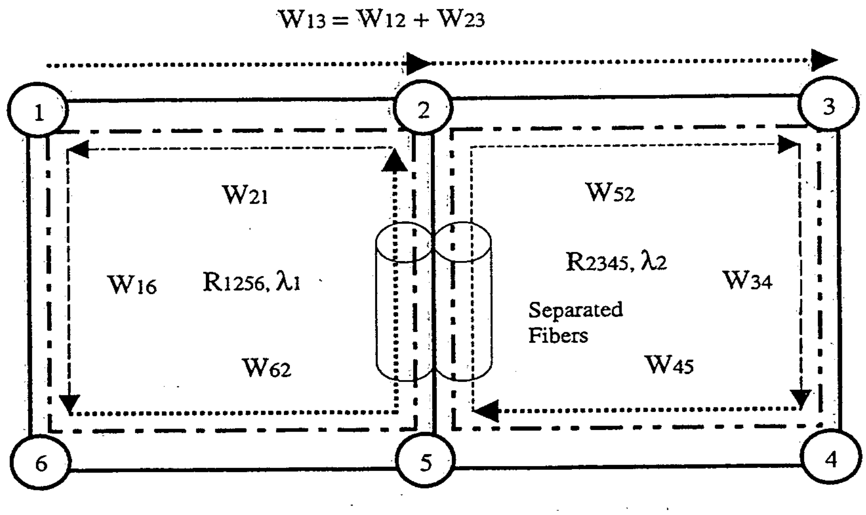

Figure 4.2.3 Interconnected fiber rings (IFR)

4.3 Model for costing

The key idea in this algorithm is to construct a cost model for each network resources, such as λ–channel and cross-connect, such that the least cost path for each demand results in a near optimal global solution. By repeated adjustment of the costs and rerouting, if necessary, one could try to optimize the solution in an asymptotic manner.

4.3.1 Marginal cost of a circuit

All our protection models are for 100% restoration for single node/link failures. That is, once a failure happens, all the affected circuits are to be restored by activating their protection paths. We use the end-to-end path protection scheme, as defined in Section 2.2.

Our routing and wavelength assignment problem can be formulated as follows: for each circuit, find the working path r_{sd}^w, the protecting paths r_{sd}^p and the wavelength w assigned, such that the circuit cost is minimized. We define the **marginal cost of a circuit** as:

$$\Psi_{sd}(w, r_{sd}^w, r_{sd}^p) = \sum_{(i,j)\in r_{sd}^w} p_{ij}(w) + \sum_{(i,j)\in r_{sd}^p} p_{ij}(w) + \sum_{i\in r_{sd}^p \cup r_{sd}^w} C_i^x$$

Where, r_{sd}^w and r_{sd}^p are two disjoint paths from node s to node d; $p_{ij}(w)$ is the channel cost function, and C_i^x is the port cost function. These cost functions will be described below. Now, the routing algorithm is simplified to routing each circuit along a path with minimum marginal cost.

4.3.2 Port cost model

We use a cost function similar to the one used in Section 3.3. Let X be the number of ports in each cross-connect. Whenever a node is short of ports, that node has to be installed with new X ports, that is, a whole cross-connect, rather than one port has to be provided. Therefore, to fully use a cross-connect, packing up to multiples of X ports in full cross-connects at each node may result in a lower cost network. In this section, we try to give a cost model for the port. The idea is

to give a high cost to the first port of a new cross-connects and a low cost to unused existing ports to encourage their use. We use the following port cost function at node i:

$$C_i^x = \begin{cases} p^x(1+1/X) & \text{if } N_i^x \bmod(X) = 0 \\ p^x / X & \text{else} \end{cases}$$

Where, p^x is the cost per cross-connect, N_i^x is the total number of ports used at node i, X is the total number of ports in a cross-connect.

4.3.3 Channel cost model

We use an incremental cost model for weighting the links as a function of their utilization similar to what was discussed in Section 3.3. For this purpose, the following cost model is introduced:

$$p_{ij}(w) = l_{ij} g_{ij}^t(w) y_{ij}(w) + l_{ij}$$

Where l_{ij} is the length of the link (i, j), the t in $g_{ij}^t(w)$ represents the protection type, $g_{ij}^t(w)$ is a protection type dependent cost factor, $y_{ij}(w)$ is a decreasing function as w increases from nW (empty fiber) to $(n+1)W$ (fully used fiber), which has the same shape as the function y shown in Figure 3.1 in Section 3.

The first term $l_{ij} g_{ij}^t(w) y_{ij}(w)$ expresses the cost of a new wavelength, and the second term l_{ij} is the length cost. The new wavelength term in the expression gives a higher cost whenever a new wavelength is needed and a much higher cost whenever a new fiber is needed. When this cost term is in effect, *i.e.*, for a new wavelength in a new fiber, it will dominate the length cost. We can ignore the length cost whenever the new wavelength cost is in effect.

The function $y_{ij}(w)$ will encourage the use of an existing fiber rather than adding a new fiber, and $g_{ij}^t(w)$ will encourage the use of an activated λ–channel rather than a new λ–channel when shared protection is allowed. $y_{ij}(w)$ is defined by:

$$y_{ij}(w) = \frac{c_{ij}\left(1 - \frac{w \bmod(W)}{W}\right)}{(w \bmod(W) + 1)^n} + h_{ij}$$

For the dedicated protection model, we define c_{ij} as:

$$c_{ij} = \frac{\sum_{(s,d)\in E} l_{sd}}{\min_{(s,d)\in E} l_{sd}} h_{ij}$$

Where E is the edge set of the network. Then, if $w \bmod (W)$ is not zero, it follows that,

$$y_{ij} l_{ij} >> h_{ij} l_{ij} >> |E| l_{ij}$$

Where, $|E|$ is the number of edges of G. We select h_{ij}^r as:

$$h_{ij}^{r} = \frac{\sum_{(s,d)\in E_r} l_{sd}}{\min_{(s,d)\in E_r} l_{sd}}$$

Where E_r is the edge set of the r^{th} ring in G. Then, if $w \pmod W$ is not zero, it follows that,

$$y_{ij} l_{ij} >> h_{ij} l_{ij} >> N_r l_{ij}$$

Therefore, the length term in the link cost function $p_{ij}(w)$ can be ignored whenever $g_{ij}^{t}(w) \neq 0$.

For future use, we define the link status function $u_{ij}(\lambda)$, which indicates the usage status of a λ-channel on link (i, j). $u_{ij}(\lambda)$ is defined as:

$$u_{ij}(\lambda) = \begin{cases} 0, & \textit{if link } (i,j) \textit{ is not occupied by any path;} \\ 1, & \textit{if link } (i,j) \textit{ is occupied by any working path;} \\ n+1, & \textit{if link } (i,j) \textit{ is shared by } n \textit{ protecting paths;} \end{cases}$$

4.3.4 Protection type dependent cost factor

In this section we give the protection type dependent cost factor for different protection models.

1. Dedicated protection

Since there is no sharing for working or protection paths, the working path and the protection path play the same role except one is active the other is not. It is natural to give the same link cost function to both. Here, we can simply select

$$g_{ij}^{d}(\lambda) = \begin{cases} 1; & \textit{if } u_{ij}(\lambda) = 0 \\ \infty; & \textit{if } u_{ij}(\lambda) > 0 \end{cases}$$

Where d indicates the dedicated protection type, $u_{ij}(\lambda)$ is the link status function. This cost factor will force each distinct circuit to use a distinct λ-channel.

2. Correlated wavelength ring protection

In this model, a set of available rings has been generated. All circuits will be routed and protected through one of the given rings. For any circuit, the length of its protection path is the length of the ring in which the circuit is routed. The protection circuit cost defined in Section 2.4 is simply the length of the ring. We can ignore this part and consider only the working circuit. All our paths will be confined on these rings. For each circuit now we have at most 2R paths, where R is the number of rings. Usually we will prefer to route a demand on the shortest path along a ring, however, sometime we may want to route a circuit along its longer path on a ring so as to make the ring load more balanced. We give different link cost factors depending on whether the link is used in the shorter path or longer path of a ring. The cost factor is now dependent on the ring and on the path type (longer/shorter path). For the shorter path, we model the shared protection cost factor as follows:

$$g_{ij}^{CS}(\lambda,r)=\begin{cases} 1; & \text{if } v_{ij}(\lambda,r)=1 \text{ and } u_{ij}(\lambda)=0; \quad \lambda-\text{channel is available to this link } (i,j) \\ \infty; & \text{if } v_{ij}(\lambda,r)=0 \text{ or } u_{ij}(\lambda)\neq 0; \quad \lambda-\text{channel is already occupied} \\ \dfrac{L(r)}{l_{ij}}+1; & \text{if } v_{ij}(\lambda,r)=0 \text{ and } u_{ij}(\lambda)=0; \quad \lambda-\text{channel is newly assigned to } r \end{cases}$$

For the longer path, we give the following cost factor:

$$g_{ij}^{CL}(\lambda,r)=\frac{L(r)}{l_{ij}}g_{ij}^{CS}(\lambda,r)$$

Where CS indicates Correlated ring protection and Shorter path, CL indicates Correlated ring protection and Longer path, $L(r)$ is the length of ring r, $v_{ij}(\lambda,r)$ indicates whether the λ-channel is already used by ring r.

3. Separated fiber rings protection

This model is very similar to the correlated fiber rings model, except each ring is forced to use its own fibers rather than sharing fibers with other rings. We can get the link cost function by modifying the link cost function in the correlated wavelength rings model. In this model, each link will be ring related, given the symbol as l_{ij}^r, where r indicates the r^{th} ring. For the shorter path, we model the shared protection cost factor as follows:

$$g_{ij}^{SS}(\lambda,r)=\begin{cases} 1; & u_{ij}(\lambda)=0; \quad \lambda-\text{channel is available to this link } (i,j) \\ \infty; & u_{ij}(\lambda)\neq 0 \quad \lambda-\text{channel is already occupied} \end{cases}$$

For the longer path, we give the following cost factor:

$$g_{ij}^{CL}(\lambda,r)=\frac{L(r)}{l_{ij}}g_{ij}^{CS}(\lambda,r)$$

Where SS indicates Separated ring protection and Shorter path, SL indicates Separated ring protection and Longer path, L(r) is the length of ring r.

4.4 Algorithms

4.4.1 Flowchart

The algorithms for dedicated protection, correlated wavelength ring (CWR), separated fiber ring (SFR) and interconnected fiber ring (IFR) are all based on the same iterative routing scheme except they use different cost functions. These algorithms can be described by the flowchart in Fig. 4.4.1.

4.4.2 Description of algorithm for CWR, SFR and dedicated protection

The following algorithm can be applied to dedicated protection, correlated wavelength rings (CWR) as well as separated fiber rings (SFR), as long as a proper cost factor $f_{ij}^{r}(\lambda, r)$ is applied. We split each demand into independent units of STM-16 (by dissociating the λ-channels) and view each STM-16 as a separate 1-unit demand.

These algorithms consist of three parts:

1. Preprocess:
   - For each demand d_{ij}, find a set of shortest paths, Π_{ij}^{p} and order them by number of hops. In our test cases, 100 paths are given for each demand, *i.e.* $1 \le p \le 100$.

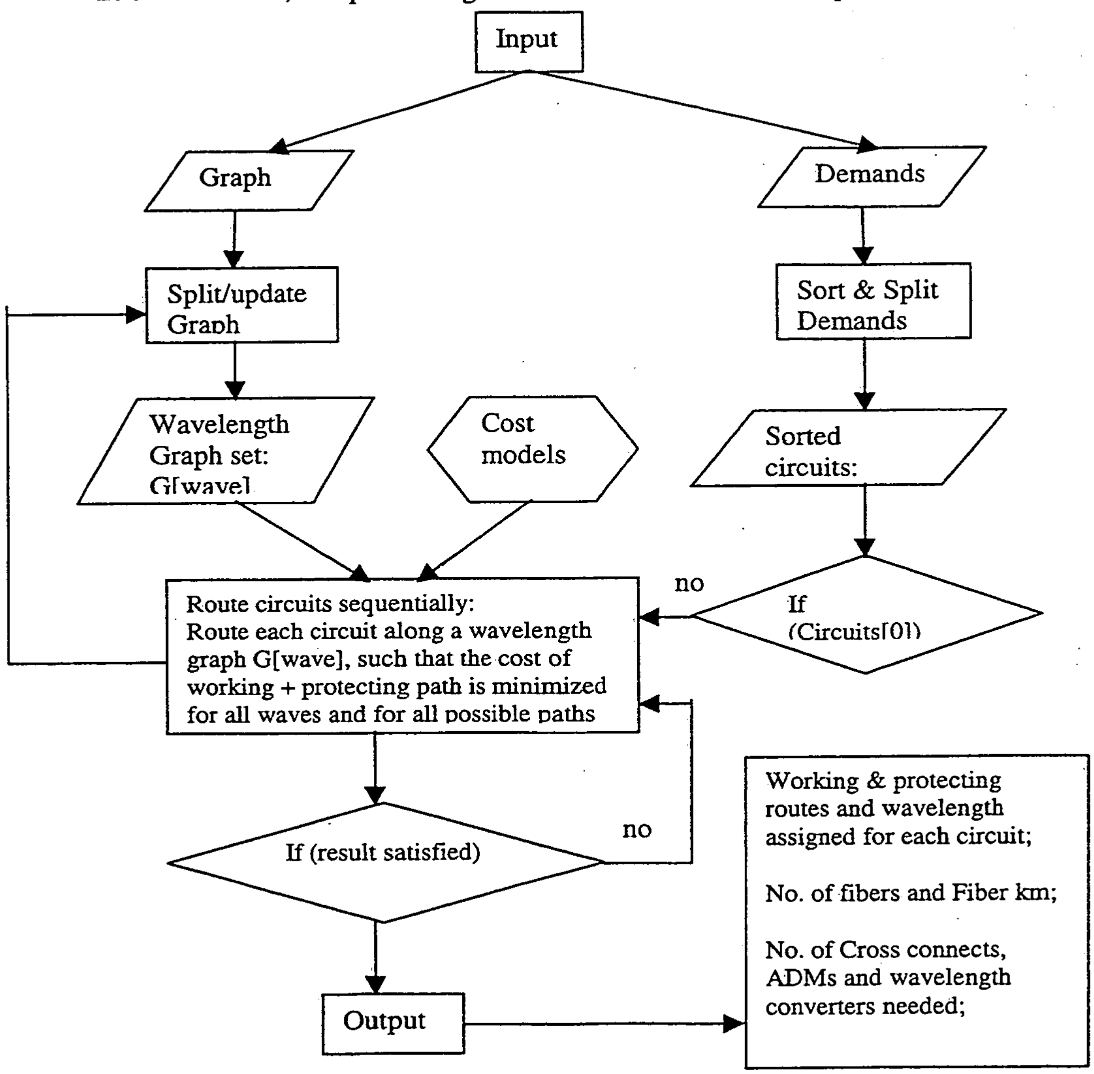

Figure 4.4.1 Algorithms for shared protection on rings

- For each demand d_{ij}, find a set of shortest rings, Θ_{ij}^r, passing through the node i and node j. In our case, upto100 rings are given for each demand, *i.e.* $1 \le r \le 100$.
- Find the set of rings Ω^R, where

$$\Omega^R = \bigcup_{k_{ij} \in K} \Theta_{ij}^r$$

- Decompose each demand into multiple circuits. Each circuit is a demand with one unit of λ-channel. List all the circuits in a circuit list, s_l, where, $1 \le l \le S$, S is the total number of circuits.

2. Routing and wavelength assignment process:
   - For i := 1, 2, …, S, route the circuit s_l along two disjoint paths $r_{sd}^w(r)$ and $r_{sd}^p(r)$ and assign the wavelength w to s_l, such that the marginal cost $S_{sd}(w, r_{sd}^w(r), r_{sd}^p(r))$ is minimized for all $w \in (1,2,...,W)$ and $r \in (1,2,...,R)$. Here, the two disjoint paths $r_{sd}^w(r)$ and $r_{sd}^p(r)$ are either given directly for the dedicated protection model or along the ring Ω^r for the shared protection using logical rings.
3. Fine Tuning process:
   - Sequentially, for every circuit s_{sd} – clear the λ channel along the associated working path r^w_{sd} and protection path r^p_{sd}. Update all information on the rings and links accordingly, then find an alternate ring r and wavelength w, which give the minimum marginal cost $\Psi_{sd}(w, r_{sd}^w(r), r_{sd}^p(r))$. Reroute the circuit s_{sd} along ring r and reassign it to wavelength w.
   - Repeat rounds of the previous step (using same sequence order) until convergence is reached.
   - Sum over the total cost for all resources used in the network to compute the total cost of the network.

Other variants of this algorithm have been investigated also. These include:

- The circuit list s_{sd} can be ordered by the number of hops of its shortest path or the length of its shortest path, either in the increasing order or decreasing order. It can also be in a random order.
- We may first run the dedicated protection design algorithm described in Section 3 and then use the result to select candidate rings.

4.5 Algorithms for interconnected fiber rings (IFR)

The interconnected fiber rings (IFR) scheme is not covered by the algorithms described in the previous section. However, IFR is an important scheme in the optical network design. The basic algorithm for the IFR model involves

- Route all demands over all possible rings.
  - Run the CWR algorithm first.
  - From all the activated rings (which have at least one demand routed through), select a subset of small rings as basic rings, such that all the links on the non-basic rings can be covered by the basic rings.

- The demands which can be routed through one of the basic rings are called basic demands, otherwise, are called non-basic demands. Since every non-basic ring can be covered by one or more basic rings, we can always decompose a non-basic demand into a set of basic demands. Decompose non-basic demands into a set (as small as possible) of basic demands.
- Select the smallest complete set of basic rings as our fiber rings.
- Route all the decomposed demands via basic rings.

4.6 DWDM network design using shared protection on rings

We have experimented with the algorithm described above on the study network described in Section 2.8, using separated rings and correlated rings algorithms. Since correlated rings are always no worse than separated rings, due to ability to shared fibers, we only report the results for the former.

5 Design of Mesh DWDM Networks via Restoration With OXCs

5.1 Outline

We describe a method to design mesh networks with point-to-point DWDM systems in which restoration is provided via optical cross-connects and preprovisioned (restoration) routes and wavelengths. We describe a few alternative formulations and show that the proposed scheme lends itself to solutions optimizing a variety of cost objectives. For example it is possible to use this method to obtain designs with 100% restoration (or any pre-specified percentage for each demand) in which the maximum number of wavelengths carried through any link is minimized, or an alternative design with the same restoration percentage in which the sum of all wavelengths times link distances is minimized over the whole network. These designs are then used to compare the advantages of alternative architectures for DWDM designs described in Sections 3 and 4. Section 5.2 provides a description of an OXC-based mesh network, Section 5.3 reviews the input data together with general formulations of the mathematical programming models and solution procedure.

5.2 Network description

We assume the network is given in the form of a graph consisting of nodes, edges and distances on edges, as described in Section 2.6.

For OXC-based mesh design, we assume each edge contains zero or more fiber pairs each of which carries up to W wavelengths, or W λs, in each direction. Each λ carries a given bandwidth (0.5gbps, 2.6gbps or 10gbps). Each node contains wavelength converters and optical cross-connects. Figure 5.1 shows this schematically for two nodes and two wavelengths per fiber, *i.e.*, W=2, and a pair of DWDM systems between them.

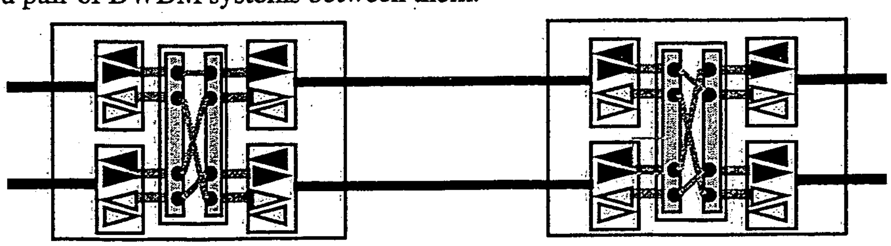

Figure 5.1 Details of eight 2λ DWDM system terminations on two OXCs

The diagram shows that each fiber terminates on a DWDM multiplexer where all λs are demultiplexed, each λ is converted into a standard λ for cross-connection purposes, is fed directly into an optical cross-connect, and converted back to any λ. The OXC connects each input port λ to the appropriate output port λ where a matching DWDM multiplexer picks up to W λs into another fiber terminating on the node. Of course, λs can be dropped or added from the OXC as well. We assume each OXC can store a variety of I/O maps in its memory. Under normal operations, the DWDM systems are configured in such a way that node pair demands are met. Node pair demands are the network loads in units of λ. OXCs provide flexibility in the network by making it possible to create channels between end nodes *as needed.* Rerouting is performed through either preconfigured maps stored in the OXC memory or through dynamic reconfiguration.

It is assumed that every node in the network is equipped with OXCs and that each DWDM system spans a single link in the network. Thus, to visualize the OXC-based mesh network of Fig. 2.2, one needs to replace each edge with one instance of Fig. 5.1.

5.3 Problem formulation

To re-use and extend the notation introduced in Section 2, let

N	Set of all network nodes
E	Set of all network edges
K	Set of all node-pairs
P	Set of all paths for all node-pairs
D	Set of all node-pair demands
d_k	Demand for node pair k
x_p	Flow (in units of λ) assigned to path p
P_k	Set of all paths for node pair k – assumed to be (node) edge disjoint
Q_e	Set of all paths that include edge e
C_e	Capacity (in number of λ s) on edge e
l_e	Distance of edge e
y_p^f	Flow (in units of λ) assigned to path p when edge f is in failure mode

To ensure that bi-directional demands are routed the same way, we restrict $(i, j) \in K$, to $i < j$. Furthermore, to reduce problem dimensionality, we include a path in P only if its end nodes have demand. To ensure that restoration from failures does not require fault *isolation,* we assume paths in each P_k are disjoint for each commodity k. Therefore, when an end node pair recognize a fault in (one of) their primary path(s), the node pair initiate restoration over the remaining paths, which due to their being disjoint from the failed path, must be operational in cases of single (link) failures.

To see how the mesh network should be designed and its demand routed using the above notation, consider the following problem [23]:

$P0: \ Find \ x_p \quad \forall p \in P$

(1) $\quad \sum_{p \in P_k} x_p \geq d_k, \quad each \ k \in K$

(2) $\quad \sum_{p \in Q_e} x_p \leq C_e, \quad each \ e \in E$

These conditions ensure that 1. Demand for each node pair k is met, and 2. The link capacities are not exceeded. Thus any allocation of flow x_p to path p that meets (1) and (2) is considered feasible. To avoid solutions with meandering paths–those that are either unusually long or visit the same node more than once–the set of paths P need to be carefully generated. Examples include paths that do not exceed pre-specified hop counts or distance limits between their end nodes. Further, more careful path generation reduces the problem complexity as will be seen in the following discussion. In general, K-disjoint paths that meet path qualifications are generated for each node pair with non-zero demand, for a sufficiently large K.

The *mesh network routing problem* can be formulated according to a variety of criteria using the foregoing notation. For example, it may be important to route as much of the demand on shortest possible routes. In this case the natural criterion may be the sum of wavelengths times the distance each wavelength traverses. Or it may be desired to spread the load as evenly as possible so that all the edges in the network carry more or less the same number of wavelengths. For the latter criterion, the following formulation results:

$P1: (even\_load = \Lambda)$

$Minimize \ \Lambda$

$Subject \ to:$

(1) $\quad \sum_{p \in P_k} x_p \geq d_k, \quad \forall k \in K$

(2) $\quad \sum_{p \in Q_e} x_p \leq C_e, \quad \forall e \in E$

(3) $\quad \sum_{p \in Q_e} x_p \leq \Lambda, \quad \forall e \in E$

Constraint set (1) ensures that demands (in number of λs) are met for each node-pair and (2) the link/DWDM capacities are not exceeded. Constraint set (3) is there to even out the load on the network. The same routing design problem, with the minimum sum of wavelength distances as the objective function is as follows:

$P2:(\lambda * dist)$

$$Minimize \quad \sum_{e \in E} \lambda_e * l_e$$

$Subject\ to:$

(1) $\sum_{p \in P_k} x_p \geq d_k, \quad \forall k \in K$

(2) $\sum_{p \in Q_e} x_p \leq \lambda_e, \quad \forall e \in E$

(3) $\lambda_e \leq C_e, \quad \forall e \in E$

Constraint set (3) for P2 counts the number of wavelengths used on each edge for use within the objective function. We will show computational results based on each of the above two criteria in Section 6.

For the mesh network restoration problem, the same set of objective functions as *P1* and *P2* apply. However, this time additional constraints are needed to ensure 100% protection against failure is also provided. Let y_p^f denote the overflow assignment of wavelengths to path *p* when edge *f* is in fail condition. Then, the assignment of normal routes x_p and restoration routes y_p^f for the minimized sum of wavelength*distance objective (as in *P2*) is given by the solution of

$P3(\lambda * dist)$

$$Minimize \quad \sum_{e \in E} \lambda_e * l_e$$

$Subject\ to:$

(1) $\sum_{p \in P_k} x_p \geq d_k, \quad \forall k \in K$

(2) $\sum_{p \in Q_e} x_p \leq C_e, \quad \forall e \in E$

(3) $\sum_{p \in Q_e} x_p \leq \lambda_e, \quad \forall e \in E$

(4) $\sum_{p \in P_k - Q_f} y_p^f \geq d_k, \quad \forall f \in E, k \in K$

(6) $\sum_{p \in Q_e - Q_f} y_p^f \leq \lambda_e, \quad \forall e \neq f \in E$

(5) $\lambda_e \leq C_e, \quad \forall f \in E$

We refer to this formulation as the restoration problem. Note that in this formulation for each failure condition a large number of reconfigurations may be necessary since the overflow variables are only constrained to meet demand and not exceed edge capacities. To enforce reconfiguration only for routes that are affected by the failure condition, a slightly different set of constraints are needed. This formulation is given below.

$P4(\lambda * dist)$

$Minimize \quad \sum_{e \in E} \lambda_e * l_e$

$Subject \ to:$

(1) $\sum_{p \in P_k} x_p \geq d_k, \qquad \forall k \in K$

(2) $\sum_{p \in Q_e} x_p \leq \lambda_e, \qquad \forall e \in E$

(3) $\lambda_e \leq C_e, \qquad \forall f \in E$

(4) $\sum_{p \in P_k - Q_f} y_p^f + \sum_{p \in P_k - Q_f} x_p \geq d_k r_k, \qquad \forall f \in E, \forall k \in K$

(5) $\sum_{p \in Q_e - Q_f} y_p^f + \sum_{p \in P_k - Q_f} x_p \leq \lambda_e, \qquad \forall e \neq f \in E$

Note that in formulation *P4* of the restoration problem, we have also allowed a more general recovery percentage r_k for each node-pair k than recovery of all paths disrupted by each link failure, $r_k = 1$ or 100% recovery, which is what was done in P3. However, this extension adds no complexity to the problem and substantially simplifies the execution of restoration.

5.4 Mesh network restoration solutions

It goes without saying that restoration is a harder mechanism to perform in a network during failure modes than other recovery scheme such as ring path recovery and dedicated protection. In compensation, restoration makes up for this complexity through savings in total bandwidth, or wavelength needed, in the solution. To see this effect at work, we solve P3 for a specific network under a few alternatives and optimization objectives.

Before describing the solutions, a few important factors need to be considered. First, problem P3 involves *~P*E* columns and *~K*E* rows for the "A matrix" of the LP, but A has only a small number of non-zero entries so that there is a good chance for a fast LP solution, as indeed is the case for our test cases. Secondly, for the LP solution we will relax the integrality constraints and round up the flows if and when needed, which turns out not to be needed for more than 95% of the flows, with negligible impact on the solution. Thirdly, The rounded up LP optimum and the optimal solution are *capacities* needed for the flow assignments which is all that is needed when wavelength converters are available. Postprocessing will be needed to translate the capacities into a complete routing with fixed wavelength assignment solution, if wavelength continuity is required. However, as argued before, in the optical backbone or core of a network, use of wavelength converters is normal, while for the (as yet futuristic) local area optical networks, or *optical enterprise networks*, wavelength continuity may be a requirement.

The network under study has 29 nodes and 53 edges. There are 137 demands between nodes most for a few λs but about 10% of these demands are in 10s of λs. DWDM system is assumed to carry 80 λs per fiber. 80 paths per node-pair were generated and P3 was formulated for this problem and solved. The LP had 9980 rows, 507621 columns, and 3963031 nonzeros. The LP was solved on Cplex6.0.2 in 498.61 seconds after 2346 pivot operations for both high and low demand scenarios. Only a small fraction (<5%) of the flows, primary or overflow, was non-integer and rounding these to integer values had no noticeable effect on the solution. We note

that essentially the same solution can be generated with as few as 5 disjoint paths per node-pair. The solution time for the resulting LP is about 2 seconds. Faster ε-approximations [5,33,41,42] of these LPs can reduce computation time to a fraction of a second.

6 Comparisons and Conclusions

The following two tables show the solutions obtained for each of the proposed architectures for the sample network of Section 2.6. Table 6.1 details the key characteristics of each solution as measured by several quantitative and qualitative metrics. Chart 6.2 provides the cost of each solution broken down by network component. All but one of these solutions assume wavelength conversion at every intermediate nodes. The correlated ring solution with wavelength continuity does not assume the use of wavelength converters, see Table 6.1. This type of solution is appropriate for metropolitan networks where distances are relatively short, while for core long distance networks use of wavelength converters will be normal practice since wavelength conversion takes place and every OXC and continuity is not yet achievable.

As it can be seen from Tables6.1-2 *dedicated protection* solutions and *shared protection ring-based* designs without optical cross-connects would provide the most cost-effective solutions. However, with optical cross-connects added–which are almost certainly required for robustness and flexibility purposes in the core of optical networks–*mesh restoration-based shared protection* architectures would be the most cost-effective. From the standpoint of recovery time, dedicated protection solutions, for the immediate future, have an advantage over the alternative designs, with the shared-protection ring-based designs closely behind. Mesh restoration in the (near) future is likely to be the architecture of choice due to its flexibility and for faster provisioning.

Based on the results shown in Table 6.1 and Chart 6.2, we also observe that:

- *Fibers and repeaters* constitute a small fraction of the total cost of each network architecture (Table 6.1 and Chart 6.2).
- *Termination costs* dominate the total cost of the network, followed by the cost of OXCs in all architectures studied (Table 6.1 and Chart 6.2).
- As long as growth is *linear*, as in the example network, the simple solution involving dedicated protection with shortest path routing is only ~30% more costly than the more complex solution involving restoration (Chart 6.2). This gap is likely to widen if demand grows more aggressively, *e.g.* geometrically or exponentially.
- Dedicated protection with *multi hops*, *i.e.*, a dedicated protection architecture (with or without shortest path routing) in which some fibers bypass intermediate OXC terminations, lowers the total cost by ~15%, primarily due to reduction in the number of optical terminating units (OTUs) and wavelength converters (Chart 6.2).
- The solutions obtained differ substantially with respect to their efficiency of use of the *wavelength resource*, which is the total number of wavelengths (or λ*km) used to route demands plus the total number of extra wavelengths (or λ*km) needed for 100% protection against single failures (Table 6.1).

Method / *Metric*	Shortest Path 1+1protecti	Optimized 1+1 protection	Rings with Wavelength Continuity	Rings with Wavelength Converter	Restoration with Min MaxLoad	Restoration with Min Sum λ *km
# links used	50 50	43 50	41 50	43 44	51 51	51 51
Max # XC BiDir ports	432 2160	505 2080	442 1891	257 1206	300 1500	200 1000
Total Fiber-pair $\times$ km	11253 34021	9182 32336	12068 40451	10103 32020	10511 –	10511 22839
Max # Fiber-pairs in any link	2 9	2 9	4 11	2 9	1 3	1 4
Total # BiDir λ's	2623 13115	2799 13118	2812 12935	2471 11790	2026 10130	1512 7560
Total BiDir $\lambda \times$ km	475958 2329790	519181 2414325	527110 2502985	470247 2276090	409297 2046485	286240 1431200
Max # BiDir λ's in any link	139 695	160 703	159 709	136 711	43 215	59 295
Ratio of #working BiDir λ's %	– –	38% 40%	44% 47%	47% 48%	69% 69%	82% 82%
Total # working BiDir λ's $\times$ km	– –	196681 958325	233452 1174830	218480 1091010	282415 1412075	234717 1173584
Recovery Speed	***	***	**	**	*	*
Operational Complexity	***	***	**	**	*	*
Reconfigurability	**	**	*	*	***	***
Reliability	***	***	**	**	*	*
Restoration Time Frame	***	***	**	**	*	*

Table 6.1 Score of each architecture/solution as measured by a variety of metrics (the top entry in each cell is the value for demand matrix of year 1 and the lower entry is for demand matrix of year 5, which is 5 times that of year 1). The qualitative scores *, **, *** stand for adequate, good and high in the bottom five rows of this table.